Phase space painting and $H^-$ stripping injection

C. Bracco on behalf of M. Plum
Why do we need phase space painting?

For hadrons the beam density at injection can be limited by space charge or by the injector capacity.

If we cannot increase the charge density, we can fill the horizontal phase space to increase the overall injected intensity IF the acceptance of the receiving machine is larger than the delivered beam emittance.

Disadvantages:
- Reduced aperture due to the septum
- High beam losses from the circulating beam hitting the septum
- Limit number of injected turns $\Rightarrow$ limited intensity

Conventional multi-turn injection
Charge exchange injection - what is it?

Electrons are stripped off the incoming beam
Chicane magnets merge the incoming beam with the circulating beam

Injection chicane
Charge exchange injection – who cares?

- Charge exchange injection (CEI) is the only way to achieve low loss multi-turn injection into a synchrotron or storage ring
  - Best loss achieved without CEI = ~10%
  - Best loss achieved with CEI = ~0.02%
- Beam loss is important, especially for high power beams
  - 10% of 1 MW beam is 100 kW, not possible to have this much beam loss in the injection area
- CEI is the only way to stack many turns without linear growth in emittance
  - $\varepsilon_{\text{TOTAL}} < N * \varepsilon_{\text{INJECTED}}$
  - CEI is a good way to make high density beams
- Only practical way today is to use stripper foils, but these become complicated for high beam powers...
- This talk will focus on $H^-$ charge exchange injection
First charge exchange injection by BINP / Novosibirsk in 1966 - used gas jets

• Small Radius- High beam density. Revolution 5.3 MHz. 1 MeV, 0.5 mA, 1 ms.


1 - First stripper
2 - Main stripper pulsed supersonic jet
3 - Gas pumping
4 - Pickup integral
5 - Accelerating drift tube
6 - Gas luminescent profile monitor
7 - Residual gas current monitor
8 - Residual gas IPM
9 - BPM
10 - Current monitor
11 - FC
12 - Deflector for suppression transverse instability by negative feedback.
First use of stripper foil for CEI at Argonne, 1972

Stripper foil mechanism located just downstream of C magnet
50 MeV H\(^-\) beam from linac

Booster I
Stripper foil assembly used at Argonne test booster for ZGS

Polyparaxylene foil, 35 μm thick, ~36 x 100 mm

- Rotating disk, ~0.9 m dia., 1800 rpm, synchronized with 30 Hz booster cycle
- Foil is only in path of beam during injection
- Expected foil lifetime 2 hours

The world’s first stripper foil was also the world’s most complicated - but it worked amazingly well!

A. J. Gorka, PAC’73
Brief history of $H^-$ injected beam power

- BINP [1966]
- Argonne ZGS Booster I [1972]
- Argon ZGS [1976]
- FNAL booster [1978]
- Argonne IPNS [1981]
- BNL AGS [1982]
- ISIS [1984]
- LANSCE [1984]
- KEK Booster [1987]
- DESY 3 [1990]
- BNL Booster [1991]
- FNAL Booster upgrade [2006]
- SNS [2006]
- J-PARC RCS [2007]
- CSNS [2017]
- CERN PSB (after upgrade) [2021]

Injected beam power [kW], logarithmic axis

- 1.5 MW
- 80 kW
- 133 kW
H⁻ injected beam power

- 1 MW
- 10 kW
- 0.1 kW

H⁻ avg current [mA]

H⁻ beam energy [MeV]

- SNS
- LANSCE
- J-PARC
- ISIS
- FNAL Booster II
- SNS upgrade
- BINP
- CERN PSB (2021)
Interesting example where both multi-turn (He ions) and charge exchange injection (H ions) is possible with the same machine

(from I.Sakai et al., EPAC96)
Injected beam parameters

- We want the injected spot size to be small because this will result in fewer foil hits by the circulating beam
  - Upright ellipse: the Twiss parameter for this condition is $\alpha_{ix} = \alpha_{iy} = 0$.
- We also in general want the dispersion of the injection beam line to be zero,
  - to minimize the beam size, and
  - to prevent the beam from moving due to linac energy fluctuations or due to the longitudinal painting process
  - The Twiss parameters for this condition are $D_{ix} = D_{iy} = 0$
Phase space painting – what is it?

• With charge exchange injection it is easy to control how the phase space of the circulating beam is “filled up”

• It allows us to control the size and distribution of the beam
  • It can be hollow, very dense, or smooth and uniform

• The beam density can be much higher than allowed by non-CEI injection

With/without space charge

C. Prior, CAS Bilbao 2011
Example: Transverse ph.sp.painting

- Transverse painting the beam in the ring is accomplished by moving the injected and/or circulating beam during the injection process.
- This is important for minimizing foil hits (foil heating, emittance growth due to scattering) and controlling space charge effects!

(Courtesy S. Cousineau)
Charge exchange $H^-$ injection

Start of injection process
Closed orbit is moved to be close to the stripper foil

Displace orbit
Circulating $p^+$

Injection chicane
Stripping foil

$H^-$ beam
$H^0$
$p^+$
End of injection process
Closed orbit has been moved away from the stripper foil
Phase space is filled up and uniform

Ex: Ph. sp. painting (cont.)
Injection at the Primary Foil

• The size of the ring beam is determined by the distance \(d\) between H\(^{-}\) on the foil, and the closed orbit at the location of the foil.

• To control the size of the beam, we need to change the position of the ring closed orbit.
  
  • Closer to foil = smaller beam.
  • Farther from foil = bigger beam.
Example: SNS charge exchange injection

Example - SNS injection scheme

- Bump magnets
- Chicane magnets
- Stripper foil
- Injection dump beam line
Eight injection kickers provide an amplitude variable bump used to change the circulating proton beam orbit. There are 4 vertical kickers, and 4 horizontal kickers.

- To make a smaller beam, increase injection kicker voltage.
- To make a bigger beam, decrease injection kicker voltage.
The injection kickers allow turn-by-turn amplitude dependence, which gives us the ability to “paint” a beam from small to big, or any way we want.

**Goals of painting:**
- Minimize of circulating beam foil traversals. (i.e, pull the injected beam off the foil fast!). New beam is always injected at edge of the proton beam.
- Final distribution is uniform distribution (including space charge effects).

Nominal Kicker waveform

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Kicker Amplitude

Start of injection (t=0)

End of Injection

time

small

~ (1 − \sqrt{t})

big

Earlier turns are pulled off of foil.
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Injection Painting - longitudinal

• Longitudinal painting the beam in the ring allows us to achieve a high momentum spread for beam stability without introducing a momentum tail.

• The idea is to vary the injected beam energy during the injection process.

![Graph showing energy distribution](image)

Figure 2. Time integrated energy distribution using constant amplitude energy spreader cavity (black) and debuncher cavity (red).

The PSB has to provide beam to several users with very different requirements, future targets: high brightness (LHC: 1.7e12 p+ in <1 μm emittance) ➞ high intensity (ISOLDE: 2e13 p+ in 8x13 μm HXV emittance)

160 MeV H⁻ beam from Linac4

35 mm painting + 46 mm chicane
Painting in the PSB

Longitudinal painting (only high intensity beams, no LHC)

Transverse painting in H plane and vertical offset in V plane with TL steering (only high intensity beams, no LHC).

At the end of the TL $D_x \neq 0$ ($D_x = 1.4m$ in the PSB injection region $\Rightarrow$ need matched dispersion for high brightness beams!) $\Rightarrow$ longitudinal painting affecting transverse painting and foil size.
Stripper foils

• Stripper foils are the best technology available today for charge exchange injection into storage rings and synchrotrons

• Key component at many facilities
  ▪ Spallation Neutron Sources (ORNL, J-PARC, ISIS, C-SNS, PSR)
  ▪ Colliders (BNL, CERN, FNAL, …)
  ▪ Ion beams (FRIB, …)

• Some cases are easy, and you can just buy the foils already mounted

• Some cases are very demanding & specialized, like SNS and J-PARC, where the foils must be fabricated in-house
What makes a good stripper foil?

- **Thick enough** to strip off the electrons from the injected $H^-$ beam
- **Thin enough** to minimize the effect on the previously injected (circulating) beam (i.e. minimize scattering and energy loss)
- Sometimes the foil gets very hot, so it should also have a **high melting point**
- The SNS foil is also ideally supported just from the top, and we don’t want any extra material in the beam, so it should be **self supporting**
Thick enough to strip off the electrons...

- Not all incident $H^-$ are fully stripped to protons in the foil.
- The fraction of partially stripped ($H^-$ to $H^0$) beam is a strong function of the foil thickness.

Gulley et. al., PRA 53, 3201 (1996)
Stripping efficiency @ 1 GeV

\[ \sigma_{-1,0} = (6.76 \pm 0.09) \times 10^{-19} \text{ cm}^2 \]
\[ \sigma_{0,1} = (2.64 \pm 0.05) \times 10^{-19} \text{ cm}^2 \]
\[ \sigma_{-1,1} = (0.12 \pm 0.06) \times 10^{-19} \text{ cm}^2 \]

Nominal SNS foil thickness is 300 \( \mu \text{g/cm}^2 \) with 97% stripping efficiency
Thin enough to minimize impact on circulating beam...

- The average proton in the SNS ring passes through the stripper foil 6 to 7 times.
- A thicker foil will run at a higher temperature, will scatter the circulating beam, and increase the radio-activation levels.
- In thin foils a single scattering of ~100 times or more than rms scattering angle has a significant probability (much greater than from Gaussian approximation).
- Rutherford formula:

\[
\frac{d\sigma}{d\Omega} \approx \left(\frac{2Ze^2}{p}\right)^2 \frac{1}{\theta^4} = \frac{C_0}{\theta^4} \quad \theta^2 = \theta_x^2 + \theta_y^2 \quad C_0 = \left(\frac{2Ze^2}{p}\right)^2 = \left(\frac{2Zm_ee}{\gamma\beta^2M}\right)^2
\]

- If scattering angle \(\theta_x\) or \(\theta_y\) is large enough particle will be lost on an acceptance-limiting aperture.
The probability of scattering per foil traversal is

\[
P = \left( \frac{2Ze^2}{\gamma M \beta^2} \right)^2 N_0 \left( \frac{\rho t}{A} \right) \left[ \frac{1}{\theta_{xl} \theta_{yl}} + \frac{1}{\theta_{xl}^2} \tan^{-1} \left( \frac{\theta_{yl}}{\theta_{xl}} \right) + \frac{1}{\theta_{yl}^2} \tan^{-1} \left( \frac{\theta_{xl}}{\theta_{yl}} \right) \right]
\]

Want foils with low atomic number, low density and low thickness

Where \( \theta_{xl}^2 = \frac{X_A}{\beta_{fx}} \) and \( \theta_{yl}^2 = \frac{Y_A}{\beta_{fy}} \)

Are the limiting angles above which a scattered particles will be lost being \( X_A \) and \( Y_A \) the H and V machine acceptance and \( \beta_{fx,y} \) the \( \beta \) function at the foil

Carbon is a good foil material because of its low density (<2 g/cm\(^3\)), low atomic number, and can make them very thin.

Stripper foil development

• This is an area of active development, with R&D programs at labs around the world, and with workshops dedicated to this topic

• One of the biggest issues is stripper foil lifetime (e.g. SNS, FRIB, PSR, Project-X)
  - Limits the maximum achievable beam power
  - The stripper foil is like a fuse in the beam line - if you over power it, then it evaporates or breaks into pieces, and the beam shuts off
SNS stripper foil

• Front-End:
  • Produce a 1-msec long, chopped, H⁻ beam

• 1 GeV LINAC

• Accumulator Ring:
  • Compress 1 msec long pulse to 700 nsec
  • 1000 MeV
SNS foils

• 17 x 45 mm, ~0.38 mg/cm² or ~1 micrometer thick
• Stripping efficiency is ~97%
• (Balance between thick enough to strip and thin enough to minimize beam loss)

*Photos by C. Luck*
Best foil technology today

**SNS**
- Nanocrystalline diamond
- Self supporting
- (R. Shaw, ORNL)

**J-PARC and PSR**
- Hybrid boron-carbon
- Requires fiber support
- (I. Sugai, KEK)

**PSR**
- AC-DC arc discharge
- Requires fiber support
- (I. Sugai, KEK)
• Primary limits on foil lifetime are temperature and thermal stress
  - At 2200 K the carbon sublimates (evaporates) at a rate of ~1 micrometer / hour (our foils are 1 micrometer thick to start with!)
  - Vapor pressure $P(T) = Ae^{(-B/T)}$, so the sublimation rate is a strong function of temperature

\[ P(T) = Ae^{(-B/T)} \]

(SNS, 1.5 MW, 1 GeV
Courtesy Y. Zhang)
Foil temperature

- Foil temperatures are hard to model and/or calculate
  - Emissivity, heat capacity, and thermal conductivity are not well known at these high temperatures
  - Energy deposition is not well known
    - Need exact number of foil hits per injected proton (~8 or so at SNS)
    - Need to know how much energy is deposited by $H^-$ particle as it breaks up in passing through the foil
    - Need to include effects like knock-out (delta ray) electrons caused by relativistic protons striking the foil (~28% effect?)

- Foil temperatures are hard to measure
  - Need to know emissivity for conventional measurement techniques
  - Fast function of time (peak temp only lasts for ~10’s of microseconds)
  - We have observed by eye that at ~800 kW, the SNS foils get white hot (>1700 K)
  - Foil temperature measurement system developments at SNS, KEK and CERN
Stripper foil lifetime

- Biggest risk to stripper foil lifetime is sublimation
- A small temperature increase makes a big change in foil lifetime

- Sublimation rate increases by factor of 10,000 for 300 K temperature increase.
- Note: Big error bars on predicted foil temperatures! Lots of assumptions.
- Measurement of absolute foil temperature is in progress

\[ \text{Sublimation rate for carbon} \]

- 1 GeV, 1.4 MW
- 1.3 GeV, 3.0 MW

- 10% of foil disappears in 1 hour for carbon, const. temp.
Complications of CEI at high power

- Beam loss caused by foil scattering
- Stripper foil lifetime
- Control and disposal of un-stripped and partially stripped beam
- Beam loss caused by H⁰ excited states
- Stripped (convoy) electrons must be controlled too
- Damage caused by reflected convoy electrons
Beam loss caused by $H^0$ excited states

- First discovered ~1993 by R. Hutson and R. Macek at the Los Alamos Proton Storage Ring
  - Causes 15 - 20% of the total beam loss today at PSR (i.e. causes 23 - 40 W beam loss)
- If SNS design did not account for $H^{0*}$ beam loss, it would have caused up to ~2,850 W of beam loss
- J-PARC RCS has only <8 W of $H^{0*}$, not enough to require special treatment
H⁰ excited state lifetimes

• The H⁰ excited states are populated according to the \( n^{-2.8} \) law, where \( n=1, 2, 3, \ldots \) is the principle quantum number of the H⁰ atoms.

• When the H⁰\( ^* \) pass through a magnetic field, they see an electric field due to a relativistic transformation:
  - \( E = \gamma\beta cB_{lab} \)

• This electric field can strip off the electron.

• If the newly created proton is outside the acceptance of the ring it will create beam loss.

• It can be a large fraction of the total loss (e.g. at PSR it is ~15-20% of the total loss).

• SNS was designed specifically to handle these excited states.
H⁰ excited states - SNS solution

- Concern over H⁰ excited state beam loss drove SNS design team to place the stripper foil inside a strong magnetic field
- B-field immediately strips the $n \geq 5$ H⁰* states
- Also directs convoy electrons to an electron catcher
- At SNS, H⁰ excited state beam loss is too low to accurately measure

Figure courtesy L. Wang
• At SNS, low n states \((n \leq 3)\) are long-lived and can be transported along with the ground state \(H^0\) into the injection dump. High n states \((n \geq 6)\) are short-lived and are Lorentz-stripped immediately. About 0.01% of the \(n = 4\) and \(n = 5\) are lost.

• Choice of foil thickness should take into account the \(H^0\) excited states.
Control of “convoy” electrons

• We call the electrons that are stripped off the H\textsuperscript{-} beam convoy electrons
• At SNS design power, the convoy electrons carry 1.6 kW of power. This amount of power must be properly controlled.

J-PARC intercepts convoy electrons (~145 W) in chicane magnet fringe field. (Courtesy P. Saha)

Un-controlled convoy electron burn spot at PSR, due to ~85 W of electron power. (Courtesy R. Macek)
Convoy electrons - SNS solution

- At SNS the convoy electrons spiral around the magnetic field from the chicane magnet fringe field.
- At the bottom of the vacuum chamber is a water cooled electron collector made of carbon-carbon wedges.

Figure courtesy L. Wang
Reflected convoy electrons at SNS

Electron caught at catcher!

The convoy electrons are ideally trapped by this electron catcher mounted in the bottom of the vacuum chamber.

But, location of catcher is not ideal due to component fabrication error and changes to foil mount position. Some of the electrons reflect back up and hit the foil and the bracket.

Simulations by S. Cousineau
Example: damage caused by refl. e's

#1872, 3 months at 1.1 to 1.4 MW
(~20 days at 1.3 – 1.4 MW)

#2199, TZM bracket,
~16 days at 1.3 – 1.4 MW

- New TZM bracket tested Nov. – Dec. 2015
- Advantages: high sublimation temperature, low sputtering yield, high sputtering threshold
- Disadvantages: Heavy, long-lived radio-activation

Fabricating bracket from TZM instead of Ti helps. The TZM bracket shows almost zero damage.
Lessons learnt

• For hadrons the beam density at injection can be limited by space charge or by the injector capacity.
• Transverse phase space painting allows to increase the total stored intensity but the emittance increases (plus high losses at the septum!) unless charge exchange injection is used:
  ▪ Control size and distribution of the injected beam ➔ high density
  ▪ Minimize number of foil hits for circulating beam
• Longitudinal painting: modulation of the energy during injection ➔ further reduction of space charge.
• Stripping foils need to be
  ▪ Thick enough to maximize stripping efficiency
  ▪ Thin enough to minimize scattering and energy loss
  ▪ Robust! (foil lifetime main limitation to beam power)
• High-intensity charge exchange injection: need careful handling of stripped electrons and HO excited states.
Back-up slides
The lower the injection energy, the lower the magnetic fields (beam less stiff), lower beam velocity, smaller E-fields (smaller Lorentz transform E-fields), and thus fewer \( \text{H}^0 \) states with less power per state.